RECLAMATION
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Technical Memorandum No. 8540-2017-047

Coal Tar Enamel Repair Guide

U.S. Department of the Interior
Bureau of Reclamation
Technical Service Center
Denver, Colorado

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Mission Statements

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On the cover: Grand Coulee Dam Third Powerplant coal tar enamel spot repair on Unit 24 scroll case.

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Technical Service Center, Denver, Colorado
Materials and Corrosion Laboratory, 86-68540

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Coal Tar Enamel Repair Guide

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This guide includes content from a previous publication: A.D. Skaja, B.E. Merten, and D.S. Tordonato, “Coal Tar Enamel Service Life Extension,” Proceedings of the Society for Protective Coatings, SSPC 2015, Las Vegas NV, February 4, 2015. The original manuscript is reproduced and modified for Government purposes.

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Acronyms and Abbreviations

ASTM	American Standard Testing Methods
AWWA	American Water Works Association
ft^2	square feet
lb/in^2	pounds per square inch
OSHA	Occupational Safety and Health Administration
Reclamation	Bureau of Reclamation
SSPC	Society for Protective Coatings
TSC	Technical Services Center

Introduction

The American Water Works Association (AWWA) C203, type II, hot-applied coal tar enamel lining is in service on many of the Bureau of Reclamation's (Reclamation) outlet works and penstocks [2]. The enamel has provided more than 80 years of corrosion protection at facilities such as Hoover Powerplant, which was commissioned in 1935 [3]. In figure 1, the original lining for Hoover's Arizona penstock header is shown. Note the characteristic "hand-daubered" pattern at the crown.

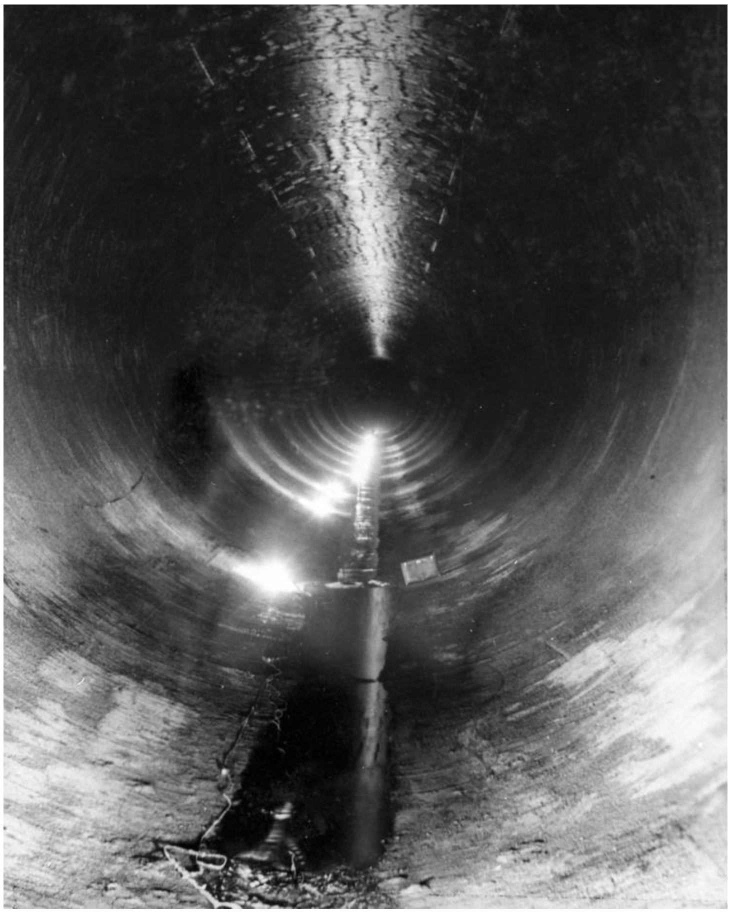

Figure 1. Completed coal tar enamel application of Hoover Powerplant's 30-foot-diameter, lower Arizona penstock header (photograph No. WASH-No-3613 from Reclamation's database).

Coal tar enamel provides an extremely long service life in continuous immersion environments. The linings in penstocks and outlet works that are buried, encased, or in tunnels maintain excellent condition with minor damage. When temperatures fluctuate between hot and cold, however, the enamel develops microcracking that progresses as service continues. As a result, Reclamation experienced reduced service lifetimes for coal tar enamel on many above ground penstocks and outlet works. The severity of the damage depends upon the frequency and duration of the exposure to the temperature fluctuations, which are most pronounced when the pipe is unwatered for long periods of time.

Reclamation facilities are tasked with regularly inspecting these coal tar enamel linings and performing maintenance in areas with insufficient corrosion protection. Once the coal tar enamel degrades to a critical point, it has to be completely removed and replaced with an alternative lining, such as a 100-percent (%) solids epoxy.

This guide defines coal tar enamel "damage" as areas of visible corrosion either from physical impact damage or coating degradation. This guide also reviews the various stages of coal tar enamel degradation and provides suggested maintenance options, with the goal of maximizing service life and minimizing coating maintenance costs. It gives recommended procedures for proper surface preparation and application of 100% solids epoxy coating spot repairs to damaged areas of coal tar enamel. (Reclamation's experience with this repair material is documented in Appendix 1, Field Performance of Modern Repair Materials.) According to laboratory investigations of the 100% solids epoxy repair's bond strength, it adheres to coal tar enamel better than other materials do. At the time of this writing, however, Reclamation has had limited field experience using it. This guide includes examples of Reclamation field experiences with coal tar epoxy and solvent borne epoxy.

For further information on coal tar enamel corrosion protection and history, refer to the following publications, which can be obtained by contacting the Materials and Corrosion Laboratory:

- Corrosion Protection of Steel Structures by Coal Tar Enamel: 80 Years of Performance [4].
- Coal Tar Enamel Service Life Extension [1].

Coal Tar Enamel Maintenance Options

The condition of coal tar enamel will change and deteriorate throughout its service lifetime. Several mechanisms can cause coal tar enamel to fail. The most common degradation is a progressive cracking that results from thermal stresses (i.e., thermal expansion and contraction). This progressive cracking results in a loss of plasticity, as low molecular weight compounds leach out of the coating, making it increasingly brittle. Coal tar enamel may also become physically damaged, causing the coating to disbond or otherwise lose its protective properties. Spalls are examples of damage caused by impact from debris. A raised coating edge is at risk of being stripped out by high velocity water. On rare occasions, coal tar enamel can also fail by blistering, possibly due to hydrogen sulfide gases produced by rotting aquatic vegetation [5].

It is important to monitor the coating condition and perform maintenance when needed to ensure that the underlying structure remains protected. Facilities have four options for maintaining coal tar enamel:

- Do no coating maintenance.
- Perform spot repairs to damaged areas or where coating is missing.
- Perform larger zone or section repairs for badly damaged or degraded areas.
- Fully remove and recoat.

The first option, do no coating maintenance, should be reserved for coatings in excellent condition, or in rare circumstances, such as when a structure no longer needs to be protected because it will soon be decommissioned. The other three maintenance options involve application of new coating material.

Spot repair techniques can be very effective in extending the service life of a structure if the lining is generally in good condition. If the surrounding coal tar enamel is not in good condition, spot repairs may not be recommended. Figure 2, taken at Grand Coulee Keys Pump/Generator Plant, shows a coal tar enamel lined discharge tube with badly degraded enamel in the pipe crown and several bands of spot repairs.

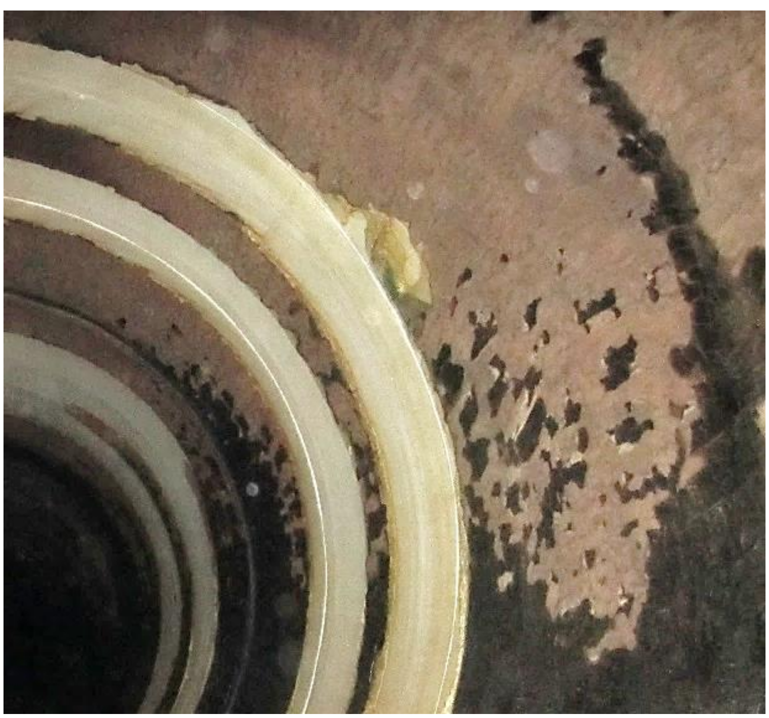

Figure 2. Coal tar enamel lined discharge tube showing badly degraded enamel in the pipe crown and several bands of spot repairs at Unit 6, Grand Coulee Keys Pump/ Generator Plant. Photo taken in the above ground section, which is subjected to fluctuating temperatures.

Procedure for Performing Condition Assessments

Assessing the condition of any coating is challenging and subjective. The primary goal of a condition assessment is to manage the corrosion protection of a given asset. The assessment should begin with a general assessment of the condition of the entire structure. After the overall condition has been assessed, a project engineer or supervisor can narrow the maintenance options. If the general condition is such that repairs are necessary, a detailed inspection should follow to identify damaged coating locations, sizes, and quantities. The next step is to analyze the data to determine the degree of repairs required. An evaluation of funds availability and an optional economic analysis complete these evaluation and feasibility stages. Consideration of all these factors ensures a technically and financially sound maintenance decision. Figure 3 is a flowchart showing a typical sequence of condition assessments and steps in project planning. Table 1 describes the general inspection rankings.

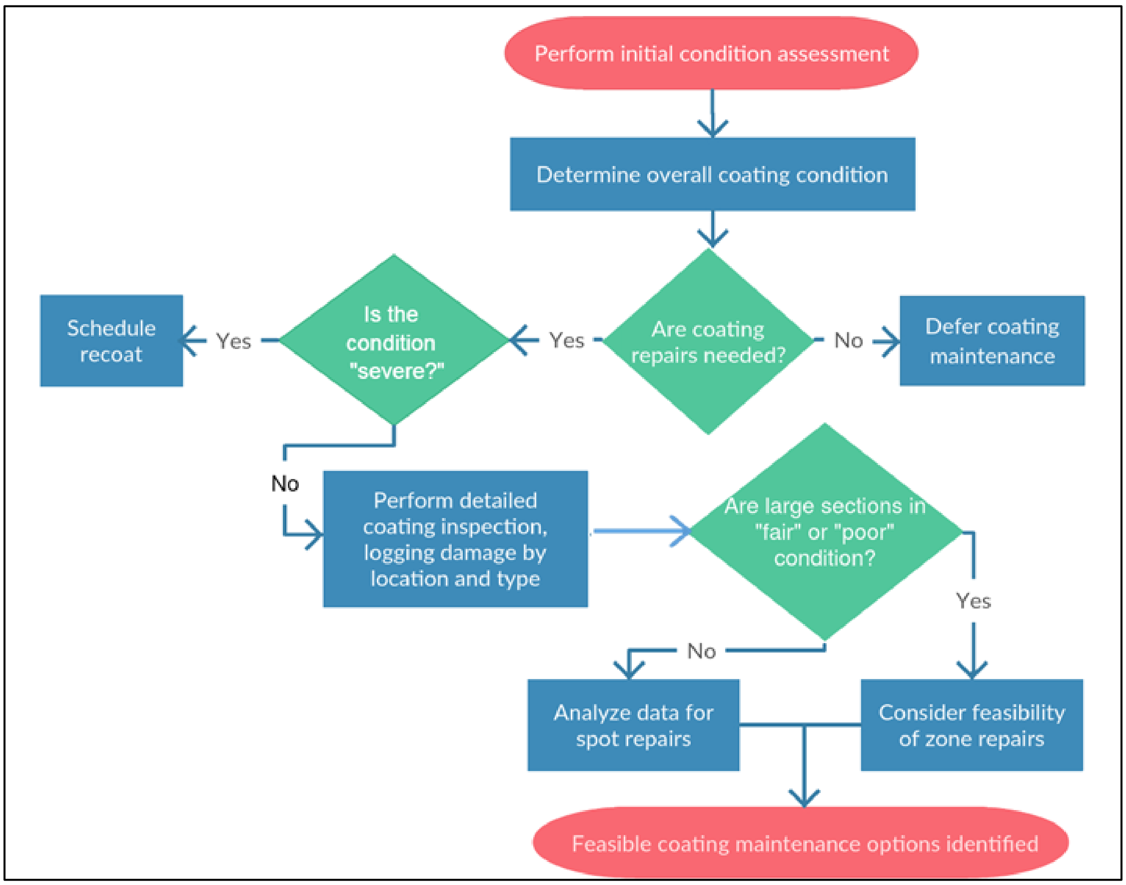

Figure 3. Flowchart for determining coating repair options.

General Inspection

An inspector should use table 1 to determine the ranking of the structure's general condition. This ranking includes a rough estimate of the total percentage of all coating damages (i.e., degradation, visible corrosion, and physical damage [macroscale assessment]). These rankings are generic and subjective to the inspector's opinion of the overall condition, but they can be used to roughly generalize the condition of the entire structure. In some instances, the structure can be split into different areas if the condition is severely damaged in one area, but good in another area, which commonly occurs when structures are subjected to multiple exposure conditions (e.g., penstocks with sections above and below ground).

Table 1. General Inspection Ranking of Coal Tar Enamel Conditions

Ranking	Description	Approximate Damage* (per 1,000 ft^2 and as percentage)
Excellent	Coating is in nearly perfect "as-applied" condition. Coating has limited visible damage.	< 1 ft^2 (< 0.1%)
Great	Coating has small damaged areas in a few locations. Coating could have some early stages of degradation with surface microcracking, but no visible corrosion.	1-5 ft^2 (0.1-0.5%)
Good	Coating has small damaged areas occurring in several localized areas. Coating could have some early stages of degradation with microcracking, but no visible corrosion.	6-10 ft^2 (0.6-1.0%)
Fair	Coating has small to medium sized damaged areas appearing in several locations or larger damaged areas in a few locations.	11-50 ft^2 (1.1-5.0%)
Poor	Coating has many small to medium sized damaged areas appearing in many locations, larger damaged areas in a several locations, or a single very large damaged area.	51-100 ft^2 (5.1-10.0%)
Severe	Coating has extensive small to medium sized damaged areas that appear widespread throughout the inspection area, or many large damaged areas	> 100 ft^2 (> 10.0%)

* The approximate damage provides a measure of the average density observed throughout the structure.
Note: ft^2 = square feet.

Detailed Inspection

Detailed inspections are comprehensive analyses that provide a greater level of detail, including quantity, size, and location of damage in an inspection log. Labeling the condition of the coating is not as important at this level of inspection because the goal is to identify all locations to be repaired. An inspector should break the structure down into smaller pieces (e.g., identify a damage location by a clock position within a pipe segment, ideally using the "facing downstream" standard convention). Table 2 shows an example of an inspection log broken down into pipe segments. Appendix 2 is a blank inspection log template. Breaking the structure down into shorter sections simplifies the inspection, making it easier to document the location and extent of damage within each pipe segment. Individual corrosion spots can also be documented by estimating the specific location using station numbers, distances, or features of the structure. This style of inspection log is not limited to pipe, penstocks, or discharge tubes. Appendix 2 also contains a blank inspection log template for localized damage areas. Labeling the type of damage at each location (e.g., blisters, cracks, spalls, corrosion, pits) makes it easier to identify later and determine if new damage has occurred.

The inspector should note the approximate total surface area of every individual spot or zone repair. It is recommended to round all areas up 1 ft^2. This is the most common minimum repair area in contract pay schedules. For example, the detailed inspection log in table shows three 6-inch-long cracks in the coating within the invert area (the 4- to 8-o'clock portion) of Pipe Segment 1. Unfortunately, there is not enough detail to determine if the coating cracks could be grouped together, or if these cracks would be classified as individual repair areas. At this point, each crack is treated as an isolated repair area and is considered to be 1 ft^2 of damage for each spot. The total damaged surface area of Pipe Segment 1 is calculated to be 10 ft^2: one crack in the crown, three cracks in the invert, and three damaged areas in both the left and right springlines.

Determining the extent of the damaged surface area can be challenging because coal tar enamel is black and absorbs much of the light source. Another limitation with large infrastructure is getting close enough to the surface to observe the degradation or small damaged areas. An inspector should strive to log defects as best as they can, knowing that there will be defects that are overlooked.

Physically damaged areas are easier to identify because a greater amount of orange rust is visible. Directly measure or estimate the size of these damaged areas. Coal tar enamel typically has excellent rust creep resistance. The size of the damage, therefore, is typically similar in size to the ensuing repair area. The coating adjacent to these repair area is often in suitable condition to accommodate the stresses of a newly applied coating.

Table 2. Example of Detailed Inspection Log of Corrosion and Defects by Pipe Segment

Pipe Segment (20 feet/ segment)	Damage by clock position				Coating Cracking by clock position				Surface Area/ Segment (ft^2)	Notes
	Crown Area (10-2)	Invert Area (4-8)	Left Spring-line (8-10)	Right Spring-line (2-4)	Crown Area (10-2)	Invert Area (4-8)	Left Spring-line (8-10)	Right Spring-line (2-4)		
1	—		3: 0.5" spots	3: 3" spots	1:12"	3: 6"			10	Segment contains the siphon breaker and temporary dike. There are anchors at 4, 6, and 8 o'clock.
2	1: 2" spot	—		—	See notes	—	3: 5"	2: 4" 1: 7"	37	Rust in cracks on the pipe crown across a 6-foot-wide swath in last 5-foot length of the pipe segment; 30 ft^2 zone repair plus seven spot repairs.
3	—	—	—	—	See notes	—	2: 12"	—	122	Rust in cracks on the pipe crown across a 6-foot-wide swath over the length of the pipe segment.
4	—	1:3" spot	—	—		—	—	—	1	Coating is in excellent condition.
Total Surface Area:									170	

Assessing the stages of degradation is the most challenging aspect of coal tar enamel because coating cracks typically have a very low percentage of corrosion or no corrosion at all. Degradation can be sporadic or widespread. Inspectors may use terms like surface cracking, minor cracking, moderate cracking, or severe cracking to state the severity or number of cracks per given area. Very early stages of degradation may only have surface cracking, where the cracks do not go down to the steel substrate (shown in figure 4). As degradation continues, the surface cracks penetrate further and further into the coating, eventually progressing all the way through to the substrate, resulting in rust in the crack. At this point, the coating condition has to be downgraded and incorporated into the total damaged area. Minor coating cracking is defined as a minimum number of very sporadic, rust-filled cracks in the coating. Minor coating cracks can be treated as a traditional spot repair, as long as the repair area can be interfaced with coating in excellent condition. Moderate coating cracks occur when the cracks become closer together in proximity. Degraded repair areas should be grouped together because the stresses of the newly applied coating could lead to additional cracking. It is necessary to completely remove the degraded section to the point where the coating is in excellent condition. Moderate to severe cracking results in large spot repairs or zone repairs because the degradation is widespread. The "Notes" column in table 2 shows a couple of examples of documented potential zone repair areas.

Figure 4. Early stages of cracking that are visible only on the coating's surface and do not penetrate down to the substrate.

One potentially useful technique to detect blisters during inspections is to hold a flashlight near the steel surface and parallel with the pipe. This technique casts a shadow for any raised surfaces, such as blisters. Although coal tar enamel rarely blisters, it has been observed.

Data Analysis and Quantifying Surface Area

After all of the damaged areas for the entire structure have been documented, a thorough analysis of the data must occur. Common practices include:

- Consider grouping damages that are in close proximity to each other into one spot repair area, rather than multiple areas.
- Salvage as much coal tar enamel as possible.
- Determine damage boundaries (where to draw the lines of the repair area).
- Determine if the surrounding coating is in excellent condition and capable of interfacing with the repair areas without further degradation.
- Make a list of priority areas, in case there is insufficient budget to conduct all repair areas.

Typically, most contracts have a minimum of 1 ft^2 area pay item. For spot repair areas that are less than 1 ft^2, the contractor receives payment for 1 ft^2. The contractor will measure the amount of coating removed, not just the size of the damaged area. This is important to remember when quantifying the total amount of surface area that requires repair. The detailed condition assessment only represents the condition at the moment it is inspected. The coating will always continue to degrade, so it is best to slightly overestimate the repairs because it may take several years before a contractor can begin work onsite.

Economics of Coating Maintenance Decisions

Direct costs are costs associated directly with the project. Most people think contract costs are the only direct costs; however, there are other direct costs associated with the project. For example, there can also be acquisitions costs, facility costs, and construction support costs associated with supporting the contractor. Direct costs can be incorporated into the economic analysis.

Indirect costs are costs that cannot be readily assessed or realized. For instance, lost revenue for hydroelectric power generation or water delivery lost during maintenance outages are indirect costs. In the context of a cost-benefit analysis, these benefits are not realized or incorporated into the economic analysis.

Coating maintenance activities are periodic and, in most cases, a coating must be replaced a number of times during the operational lifetime of a facility. As a result, additional assessments of the annualized lifecycle costs may help to determine the appropriate maintenance activity. The annualized cost is the actual "direct" cost of the coating on a "per year" basis, and an economist can help ensure that the analysis properly accounts for the time value of money.

Generally speaking, the longer a coating can be kept in service before replacement, the longer the service life and the lower the annualized cost. The cost of performing periodic maintenance activities, like spot repairs, can be effective in reducing the annualized cost. This is most often true when the damaged areas represent a low percentage of the total coated structure. The Society for Protective Coatings (SSPC) suggests that it is more economical to conduct spot repairs when coating is damaged on less than 15 percent of the surface area [6]. The actual economics for Reclamation's facilities is likely to vary as a result of site-specific cost variables; therefore, a site-specific economic analysis can help determine when spot repairs are no longer cost effective.
The economics professional and coating specialists at Reclamation's Technical Services Center (TSC) teamed up to develop a lifecycle, cost analysis spreadsheet tool that can evaluate the cost effectiveness of alternative maintenance options for recoating penstocks [7]. The challenge with any cost analysis is defining the life-cycles, whether they represent the estimated service life of newly applied coatings or remaining service life of the existing coating. The accuracy of the results is dependent on these inputs, and greater errors are possible as certainty decreases.

A few additional site-specific variables that have economic impacts for facilities are shown below for consideration. This list is not all-inclusive:

- Are the available maintenance opportunities constrained by very short outage periods?
- Is the next outage opportunity for coating maintenance years or decades from now?
- Is the coating maintenance budget available, or are there severe funding constraints or limitations?
- Is the access to the structure and grade of slope within it going to impact work production rates?
- Is the work going to be scheduled for winter months, and will the structure have proper environmental conditions for coating application?

These questions can help determine the best approaches for a facility's specific circumstances. For example, conducting spot repairs may result in shorter down times that may justify higher costs if the outage period is the priority. In another example, the longevity of the coating may be the priority because maintenance will not be possible for many years. In this case, a full recoating may be an attractive option, but there is a risk that the new coating may not last as long as the original coating would have lasted if spot repairs were conducted. There are also risks with preserving the original coal tar enamel lining because it is difficult to estimate the remaining service life.

Improvements in Coating Maintenance Techniques

It is important to stay up to date on technological advances in the coatings industry. Recent improvements in robotics resulted in the demonstration of coating removal, surface preparation, and coating application using robotic equipment. For example, the Central Arizona Project relined a 12-foot-diameter discharge tube comprised of 100,000 ft^2 of surface area in 85 days, compared to traditional methods, which would have taken much longer [8]. As the technology matures, robotics may result in higher production rates, better quality control, improved safety, and shorter outages than today's standard practices, changing the dynamics of the economics of coating maintenance.

Advances in robotic techniques for coating maintenance may also reduce the break-even point for recoating versus spot repair by traditional means. A lifecycle cost analysis can help to determine when to spot repair versus when to recoat, ensuring that the annualized cost is minimized.

Coating manufacturers are always working to improve product lines and may someday provide a spot repair material that is preferable to the 100% solids epoxy. Future coal tar enamel repair materials should have the following properties:

- Safe for personnel to apply or remove
- Good compatibility with coal tar enamel
- A service life exceeding 50 years

Maintenance Option Recommendation

After reviewing all the data and conducting an economic analysis, selecting the maintenance option may still be difficult, but will still be difficult because there is no single option that will fit every circumstance.

- Generally, if the majority of the structure is in fair to excellent condition, the recommendation is to spot and zone repair the damaged areas, thus preserving the coal tar enamel.

- In cases where there are many individual damaged areas spread sporadically throughout the structure, the lifecycle cost analysis may suggest a complete recoat, even if visible corrosion is only 5 to 10 percent. It is more time consuming and labor intensive to repair 100 individual spots that are each 1 ft^2 or less than to recoat one 100-ft^2 area, especially when multiple mobilizations are required.

- In cases of poor and severe damage, recoating versus spot repair depends upon facility decisions and whether the majority of the spots are large zone repairs. Many Reclamation facilities have opt to make larger zone repairs, even though about 25 to 30 percent of the coating was removed, to preserve as much coal tar enamel as possible. Other facilities have opted to completely reline instead of make large zone repairs.

- Project engineers and managers decide the ensuing course of action. The coating specialists will support these decisions and provide technical support to implement the work, thus facilitating a successful project.

Procedure for Performing Spot Repairs

Traditionally, coal tar enamel spot repairs could be performed using more of the same material. In the past, the areas were primed with chlorinated rubber, followed by hot enamel application with a hand dauber. The new enamel would melt into the edge of the existing coating, forming an excellent interfacial bond [3]. However, due to difficulty finding experienced applications, as well as health and safety concerns, Reclamation ceased using coal tar enamel linings in confined spaces by the mid-1980s. As a result, all future coating maintenance in these structures will require a material other than coal tar enamel [9, 10].

Appendix 1 describes experiences using modern coating materials to spot repair coal tar enamel on Reclamation structures, as well as in laboratory evaluations. Other materials may be available, or may become available in the future, making it important to occasionally revisit coating options and field results.

Identifying Repair Areas

Someone will have to identify and label every spot repair that is to be completed for the contractor to conduct the work. Figure 5 shows an example of a repair area where the coating is in good condition, with arrows pointing out the minor coating cracks and corrosion. In this particular example, the corroding defects are grouped together, resulting in two spot repair areas, rather than repairing each individual damaged area. In order to conduct successful spot repairs, the surrounding enamel has to be in excellent condition to form a transition with the new coating material. This example demonstrates minimizing the repair area, while salvaging as much coal tar enamel as possible.

Figure 5. Areas selected for spot repair should be outlined to correct all defects, while preserving as much coal tar enamel as possible.

Safety and Health

Dust from coal tar enamel is harmful and should not be inhaled or come into contact with skin or eyes during repairs. Always follow the Reclamation Safety and Health Standards manual and regional protocols [11]. Respirators with air purifying particulate cartridges may be sufficient when cleaning power tools or hand tools. Tyvek suits help prevent contamination of clothing and prevent skin contact. Good hygiene should be used to prevent accidental ingestion or inhalation of dust. Solvents should not be used to clean hands upon accidental contact with skin; always use soap and water. For abrasive blast cleaning, follow the Occupational Safety and Health Administration (OSHA) regulations using an air-supplied blasting helmet and an appropriate suit.

Surface Preparation of Existing Coal Tar Enamel

Contractors should follow the coating manufacturer's surface preparation requirements for water immersion service. Manufacturers often provide several options for surface preparation; however, not all methods may result in good preparation of the existing coal tar enamel.

The following methods are considered suitable to prepare coal tar enamel interface surfaces, and they provide approximately equivalent results:

- Abrasive blast cleaning brush-off blast (SSPC-SP7/ NACE 4) [12]
- Power tool cleaning using a bristle blaster or wire wheel (SSPC-SP3) [13]
- Hand tool cleaning using sand paper, nonwoven pad, or wire brush (SSPC-SP2) [14]

Other power tool cleaning methods result in coal tar enamel melting, fracturing, or disbonding from the steel surface. Vibration stresses from unapproved cleaning methods are thought to result in fracturing of the coal tar enamel and should be avoided.

Coating Repair Materials

At the time of this writing, laboratory and field experience suggest that 100% solids epoxies are the most compatible materials for adhering to coal tar enamel when conducting spot repairs. Not all 100% solids epoxies on the market have been evaluated; however, those that have been evaluated provided adequate laboratory results for adhesion to coal tar enamel. The following coatings have been evaluated, either in the lab or in the field, and are recommended for use in repairing coal tar enamel:

- Berry Plastics Powercrete J and F-1
- Carboline Plasite 4500S
- Con-Tech of California Hydro-pox 204
- Denso Protal 7200
- Duromar HPL 2510
- International Paint Enviroline 376F-30LT
- NSP 120
- Sherwin Williams Duraplate UHS

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Appendix 1

Field Performance of Modern Repair Materials

Appendix 1

Field Performance of Modern Repair Materials

The Bureau of Reclamation (Reclamation) used coal tar epoxy and solvent-borne epoxy to repair coal tar enamel from the mid-1980s to 2005. This appendix reports on the experienced performance of those repair materials, often after decades of service. Several failure mechanisms appear to dominate the assessments. They are described here and used as a baseline for the laboratory studies (discussed in the "Laboratory Testing" section) to ensure that future spot repairs do not present the same challenges.

Coal Tar Epoxy

The interface between these coal tar epoxy repair materials and the existing coal tar enamel is often a point of failure in these repairs. An example is shown in figure 1-1, where a coal tar epoxy coating caused cracking and failure of the adjacent the coal tar enamel. This demonstrates that a coal tar epoxy spot repair can accelerate the degradation of the surrounding coal tar enamel.

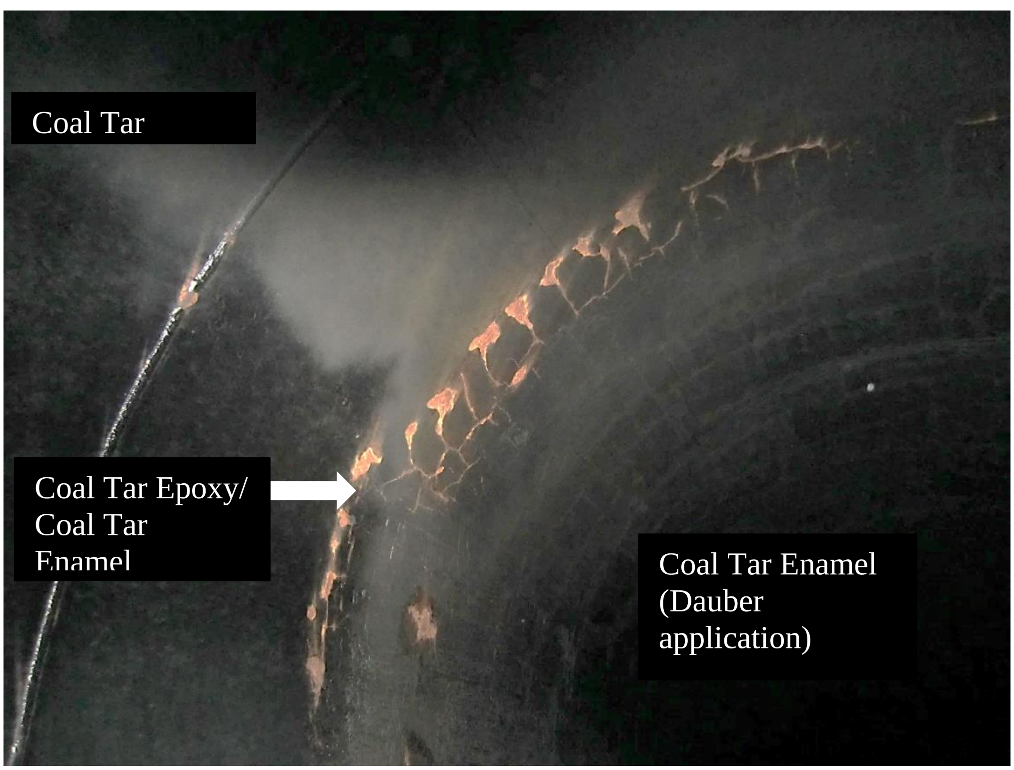

Figure 1-1. Photograph of Unit 9 discharge tube, showing corrosion at coal tar enamel/coal tar epoxy interface, Grand Coulee Keys Pump/Generator Plant.

Solvent-Borne Epoxy

Experience with solvent-borne epoxy coatings has also resulted in undesirable spot repair results. Figure 1-2 (left) shows an example of a solvent-borne epoxy coating that interfaces with coal tar enamel. Use of solvent-borne epoxy resulted in failures of the coal tar enamel lining, which negatively affected the coal tar enamel coating. Figure 1-2 (right) shows another example of a solvent-borne epoxy coating interfacing with coal tar enamel. Here, the epoxy disbonded from the coal tar enamel in one area, but no corrosion is visible, and the integrity of the enamel was not compromised. This is the desirable compatibility because there is no corrosion at the interface. Unfortunately, the type of solvent-borne epoxy coating used was not documented. The only conclusion that can be made is that solvent-borne epoxies form compatible repairs in some situations, but not in others.

Figure 1-2. Photograph of Unit 12 discharge tube at Grand Coulee Keys Pump/Generator Plant. Left: Solvent-borne epoxy/coal tar enamel interface; some coal tar enamel has disbonded. Right: Solvent-borne epoxy disbondment at the interface, but no corrosion.

Figure 1-3 provides another failure mode observed within the solvent-borne epoxy and coal tar enamel interface. This particular solvent-borne epoxy caused the coal tar enamel to bleed through the epoxy, resulting in yellowing at the interface.

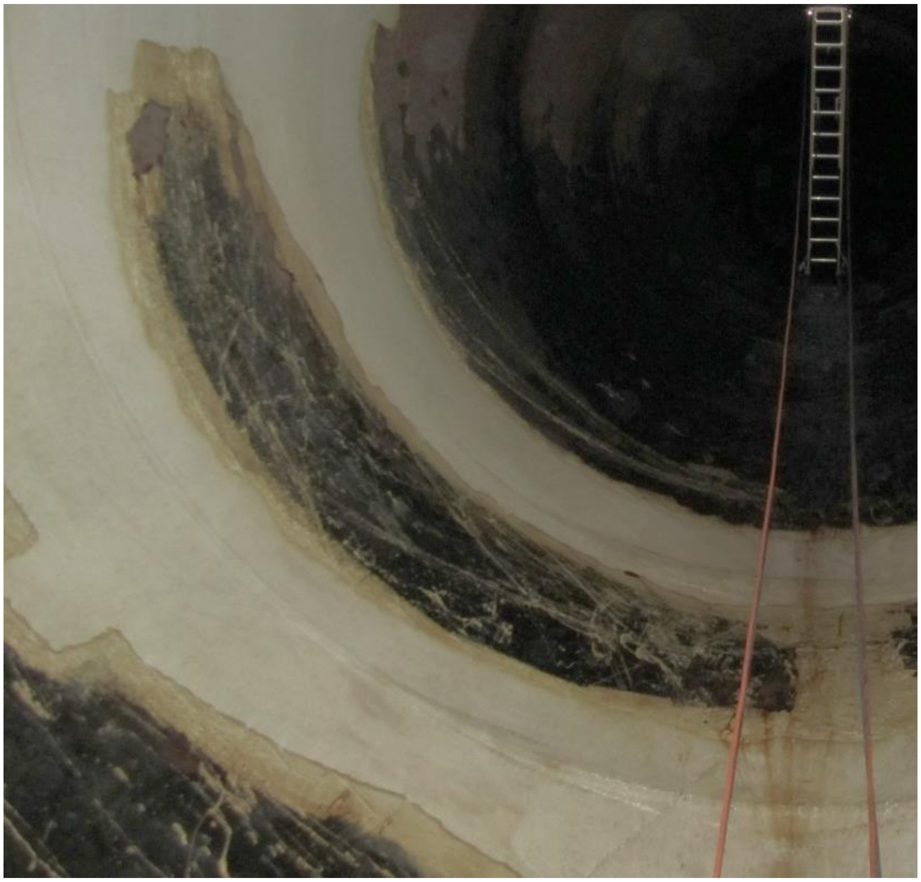

Figure 1-3. Photograph showing solvent-borne epoxy/coal tar enamel interface that has yellowed from enamel bleed-through at Unit 6, Grand Coulee Keys Pump/Generator Plant).

Because of modern coatings issues with the repair interfaces with coal tar enamel, Reclamation coating specialists worked to determine why the interfacial problems were occurring and to find alternative repair materials that may provide better success.

Laboratory Testing

Reclamation's coatings specialists evaluated coal tar enamel coated panels overcoated with modern repair materials to determine which coatings provided adequate adhesion to coal tar enamel. Seven coatings were evaluated as an overcoat/spot repair of coal tar enamel: four 100-percent (%) solids epoxies, two solvent-borne epoxies, and one coal tar epoxy. Samples were immersed in deionized water, first for 1 month and then for 6 months, to determine if water absorption affected the adhesion of these coatings to the coal tar enamel. Pull-off adhesion American Society for Testing of Materials (ASTM) D 4541, Method E, with scoring through epoxy layer showed the compatibility of the conventional coating repairs at the coal tar enamel interface (ASTM D4541-09, Pull Off Strength of Coatings Using Portable Adhesion Tester).

Results

Table 1-1 lists the results of the six measurements performed per coating system and the standard deviation. The results for the three coating types are summarized here:

- **Coal tar epoxy:** The adhesion strength was the lowest of all coatings tested at 220 pounds per square inch (lb/in^2). The solvents or oils in the coal tar epoxy softened the coal tar enamel, making the enamel turn into a gummy, tar-like material. The location of the adhesion testing failure was always deep into the coal tar enamel and, occasionally, down to the substrate.

- **Solvent-borne epoxy:** The adhesion strength ranged from 205-305 lb/in^2. The coal tar enamel failed close to the substrate, further indicating that the solvent penetrated into the enamel.

- **100% solids epoxy:** The adhesion strength ranged from 335 to 430 lb/in^2 and failed within the coal tar enamel. All four 100% solids epoxies formed mechanical bonds to the surface without reducing the coal tar enamel's integrity.

Table 1-1. Adhesion Results of Commercially Available Coatings to Coal Tar Enamel

	Adhesion to Coal Tar Enamel (lb/in^2)			Adhesion to Steel (lb/in^2)
Product Key	**No immersion**	**1 month**	**6 month**	**No immersion**
Sherwin Williams, Targuard, coal tar epoxy	220* +/-16	180*+/- 20	210 +/-22	910+/-120
International Paint, Bar Rust 233H, solvent-borne epoxy	290+/-27	210+/-24	Not tested	2590+/-400
International Paint, Devgrip 238, solvent-borne epoxy	305 +/- 18	205+/-48	315+/-48	1580+/-200
NSP 120, 100% solids epoxy	395+/-44	290+/-20	380+/-52	2730+/-270
Berry Plastics, Powercrete J, 100% solids epoxy	395**	325^	355^	1570+/-250
International Paint, Enviroline 376F-30LT, 100% solids epoxy	430+/-43	355+/-32	330+/-45	2190+/-390
Carboline Plasite 4500S, 100% solids epoxy	335+/-37	341+/-27	380+/-68	1720+/-150
Coal tar enamel	Not tested	Not tested	Not tested	350+/-5016, 17

*One of the three aluminum dollies failed while scoring.
**Standard deviations were not available.

Conclusions

This research showed that certain types of solvents reduce the cohesive strength of coal tar enamel, resulting in lower adhesion values. This reduction in coal tar enamel's integrity explains why Reclamation experiences interfacial failures with many coal tar epoxy and solvent-borne epoxy coating systems.

The 100% solids epoxies have less shrinkage during the curing process, which reduces stress and improves bond stability. Specifically, these products do not contain aggressive solvents that dissolve or permeate the coal tar enamel. Even after immersion, the adhesion values stayed above 300 lb/in^2. The laboratory results showed that adequate compatibility existed between coal tar enamel and the 100% solids epoxy, as seen in figure 1-4.

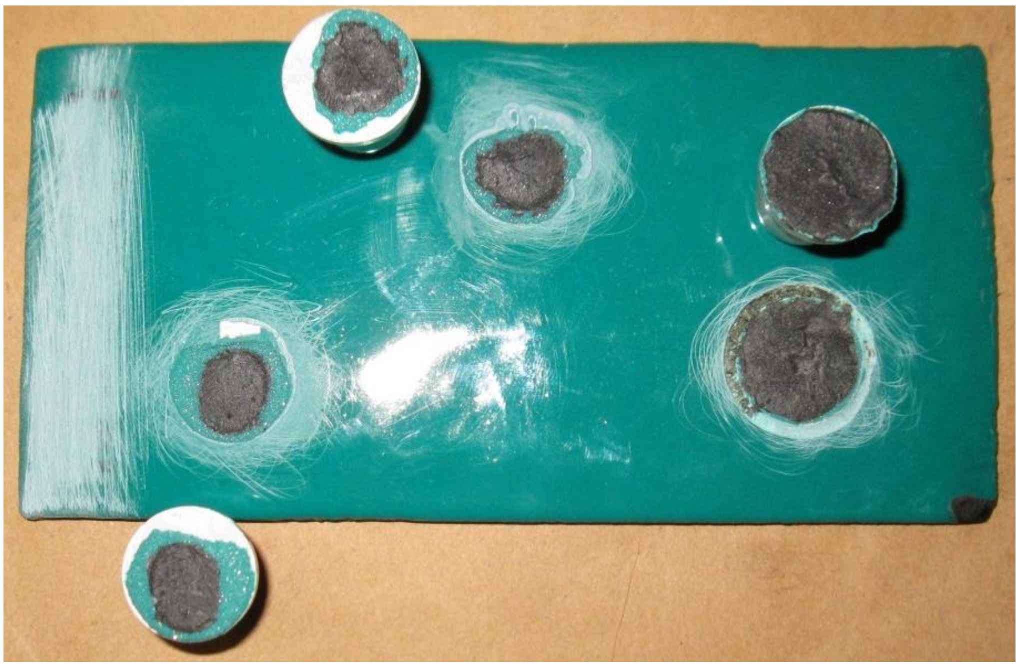

Figure 1-4. Adhesion between coal tar enamel and Powercrete F-1, depicting failure within the coal tar enamel. Black coating is coal tar enamel, turquoise coating is Powercrete F-1 (100% solids epoxy), and the white is the aluminum dolly.

Field Spot Repairs using 100% Solids Epoxy

Spot repair applications using 100% solids epoxy without followup inspections include:

- Carboline Plasite 4500S:
  - Shasta Dam, 2008: Large zone repairs in exposed penstocks, prepared by abrasive blast.

- Folsom Dam, 2013: Spot repairs in outlet work, prepared by abrasive blast and bristle blaster.

- Yellowtail Dam, 2015: Scroll case/penstock transition, prepared by abrasive blast.

- Con-Tech of California Hydro-pox 204:

  - Folsom Dam Northfork pipeline, 2010: Spot repairs of coal tar enamel at bifurcation, prepared by abrasive blast.

- Sherwin Williams Duraplate UHS:

  - Grand Coulee Dam Third Power Plant, 2014: Spot repairs in penstock and scroll case, prepared by abrasive blast.

  - Palisades Dam 2014: Spot repairs in penstock, prepared by abrasive blast.

Appendix 2

Examples of Detailed Inspection Logs

Appendix 2

Examples of Detailed Inspection Log

Pipe Segment (feet/segment)	Rust Spots by Clock Position				Coating Cracking by Clock Position				Surface Area/ Segment (square feet)	Notes
	Crown Area (10-2)	Invert Area (4-8)	Left Spring-line (8-10)	Right Spring-line (2-4)	Crown Area (10-2)	Invert Area (4-8)	Left Spring-line (8-10)	Right Spring-line (2-4)		
Total Surface Area										

Corrosion Spot	Location	Size of Defect	Surface Area (square feet)	Details
1				
2				
3				
4				
5				
6				
7				
8				
9				
10				
11				
12				
13				
14				
15				
16				
17				
18				
19				
20				
21				
22				
23				
24				
Total Surface Area				